Quadrupole R&D Phase 1

LARP Collaboration Meeting
Port Jefferson, September 16-18, 2003

Gian Luca Sabbi

LARP Magnet R&D Strategy

Main Issues/Requirements:

- High field, forces, stored energy

- Large beam-induced heat loads

- Excellent field quality

R&D plan:

- <u>Phase 1 (2003-05): Enabling R&D (design, technology, basic models)</u>

- Phase 2 (2006-09): More complex models of selected designs

- Phase 3 (2010-12): Fabrication & test of accelerator-quality prototypes

R&D Phase 1 - Motivation

1. Critical evaluation of all design/technology options

   - *Basic magnet specs are very challenging*
   - *LHC IR has additional unique requirements*

2. Basic demonstration of design/technology choices

   - *Nb_3Sn magnets are "far from fully developed"*

3. Integration of IR and magnet design optimization

4. LARP mission: "explore the limits of the technologies"

   - *LARP is a research program, not a project*

1. Design studies

- Analyze performance/features of different design options
- Identify technology issues requiring experimental investigation

2. Perform basic experiments to provide design feedback

- Conductor/cable development, coil winding
- Mechanical models, fabrication/assembly procedures
- SM-based studies (mechanics, thermal, field quality, materials…)
- Simple magnet models (to study the main design features)

3. Optimization/Iteration on IR designs

- IR and magnet optimization are tightly coupled

R&D Phase 1 - Main issues

Magnet design:

    - optimal bore size, coil geometry, support structure

Conductor R&D:

    - conductor and cable optimization for different designs

Magnet performance:

    - quench training, actual vs. expected gradient
    - design margin required for production
    - stress limits for different configurations
    - fabrication tolerances and their impact on field quality
    - strategies for operation under heavy radiation load

Optimal bore size

- AP studies: large aperture is preferred over high gradient
- However, several constraints need to be considered:

Technical factors:

- *conductor stress limits*
- *stored energy, inductance*
- *forces, magnet size*

Cost factors:

- *Coil volume vs. aperture*
- *Number of coil layers*
- *Structure, yoke requirements*

Practical optimum needs to be determined

Stress analysis (90 mm bore, 205 T/m)

- Analyzed cos2θ coils with either two layers (2L) or four layers (4L)
- Mechanical design criterion: no unloading at the pole up to $1.1 \cdot I_{ss}$

> Conductor stress at short sample (inner layer, midplane)
> 126 MPa (2L, $I_{op}/I_{ss}=0.83$); 155 MPa (4L, $I_{op}/I_{ss}=0.77$)

ASC-02, Houston, August 2002

Comments:

(+) Some room for optimization/trade-offs to decrease stress

(–) Conductor stress rapidly increases with aperture

(–) High stress point is also a high field point in *cos2q* inner layer

Performance limits under high stress needs to be investigated experimentally

The case for an early *cos2q* model

*Motivation/goal: provide input for selection of coil geometry*

- check basic design/fabrication, ***demonstrate good quench performance***
- get feedback on conductor design, quench protection and field quality
- investigate stress limits (increase pre-stress using bladders)

Must be economical:

- 2-layers, D20 tooling, dipole ends for 1/2 coils
- narrow cable, fully keystoned, no wedges
- fast bladder/key assembly (structure available)
- upgradable to a four-layer model

Parameters/Features:

- 0.7 mm strand, 8 mm cable width (SM)
- 120 mm bore, G_{ss}= 142 T/m @ 10.5 kA

Superconducting Magnet Program

Gian Luca Sabbi
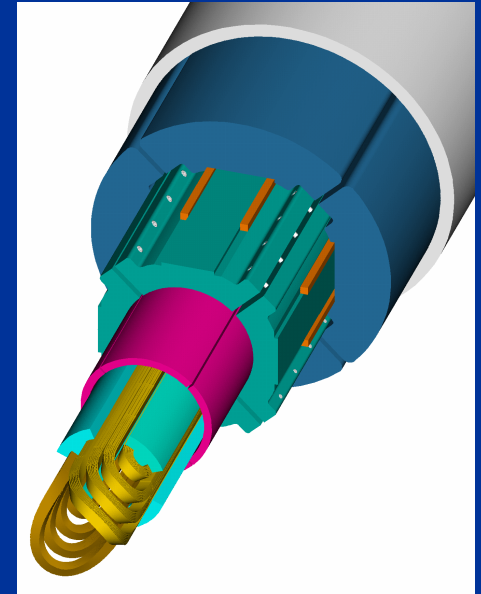
Block-coils: road to larger apertures?

Main advantages of block-coil geometry:

    - avoids azimuthal stress accumulation
    - separates high field & high stress points
    - no cable keystoning required
    - positive results from the dipole program

Issues requiring design & experimental work:

    - end spacer optimization for winding
    - minimum ratio of pole vs. cable width

Compatible with bladder/key support structure
Detailed analysis needed - also a basic model?

BLOCK-COIL DESIGN
FOR THE LHC IR QUAD
(CERN, 1991)
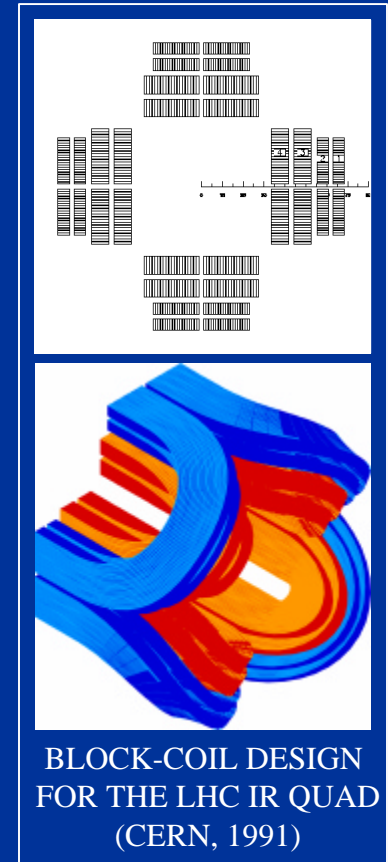
Block-coil vs. $cos2q$

Design parameters for two-layer, 90 mm aperture coils
Assuming $J_c(12T, 4.2K) = 2.4\ kA/mm^2$

Parameter	Block	cos2θ
G_{ss} (T/m)	230	247
$b_{6, 10, 14}$ @ 22 mm	< 0.05	< 0.05
Pole width I.L. (mm)	22.0 / 44.6	20.2 / 28.6
Inductance (mH/m)	4.8	4.9
Coil area (cm^2)	97.2	94.6

PAC-03, Portland, May 2003

- Theoretical gradient is -7% for block (~same coil area)
- Can be improved by grading, wider coil, higher J_c etc.
- Actual gradient determined by training, stress limits etc.

- Theoretical field quality is equivalent
- Actual field quality determined by fabrication tolerances
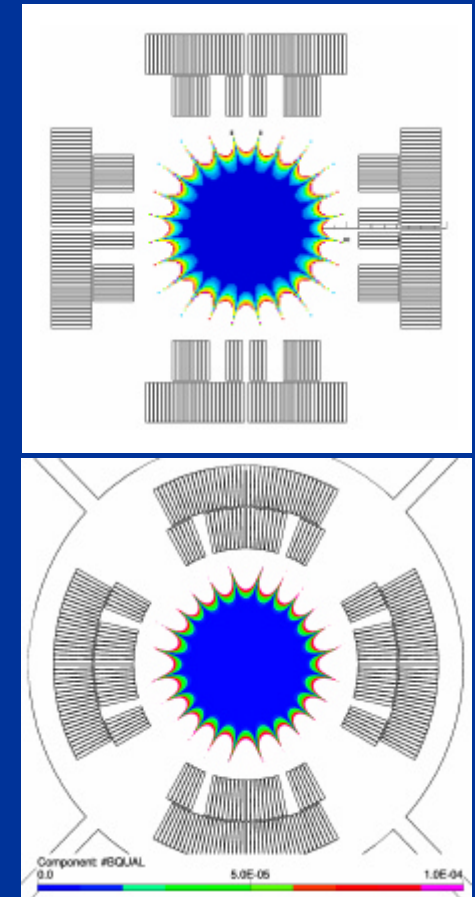
Quadrupole Field Quality

$\Rightarrow$ Excellent field quality is required at the operating gradient
(guidance on the required injection/ramp field quality is also needed)

$\Rightarrow$ Design harmonics are easily optimized to small values

The real issue: understanding fabrication tolerances in Nb_3Sn:

    - Accuracy and reproducibility of coil fabrication
    - Accuracy and reproducibility of magnet assembly
    - Achieving simultaneous control of prestress & field quality
    - Correction of systematics: coil shims, magnetic shims

Simple SM-based experiments can provide early feedback

HIF Experience with Racetrack Quads

- Under development for the heavy-ion fusion program
- Promising configuration for multiple beam transport →
- Designed by LLNL (Martovetsky, ASC-2000)
- NbTi, 4.2 K, 70 mm coil aperture, 7 T peak field
- Several cells tested at LBNL with <u>excellent results</u>
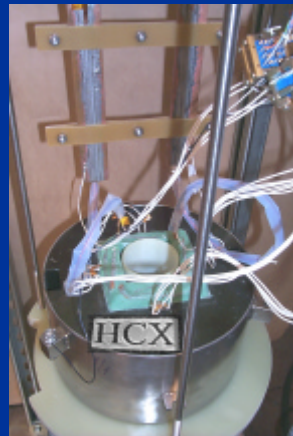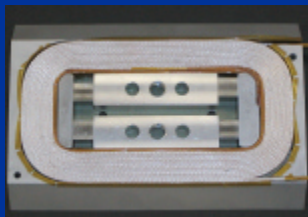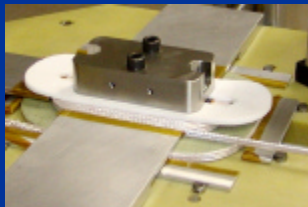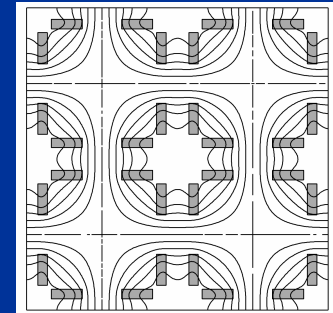
Quench performance

Prototype quad	1st Training quench $I_q^{(1)}$ /I_{ss}	No. training quench to I_{ss}
HCX-A	0.75	5
HCX-B	0.98	1
HCX-C	0.90	1

Racetrack Quads for the LHC IR?

A) for the ultimate LHC IR application

(−) Low magnetic efficiency wrt cos2θ/block
(−) Field quality is more difficult to optimize
(+) Better if aperture is measured at the midplane →
(+) Better with nested coils (Gupta, ASC-02)
(+) Inexpensive fabrication
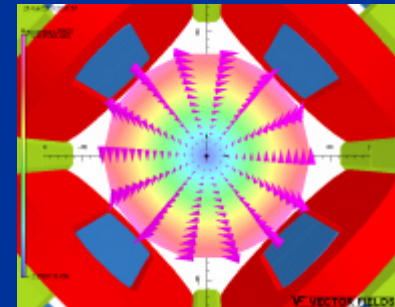
B) for technology development

(+) Easily integrates with the SM program and the bladder/key structure
(+) Cost-effective method to investigate:
  • field quality and related mechanical issues
  • materials, thermal, quench protection studies

SM-based Racetrack Quad
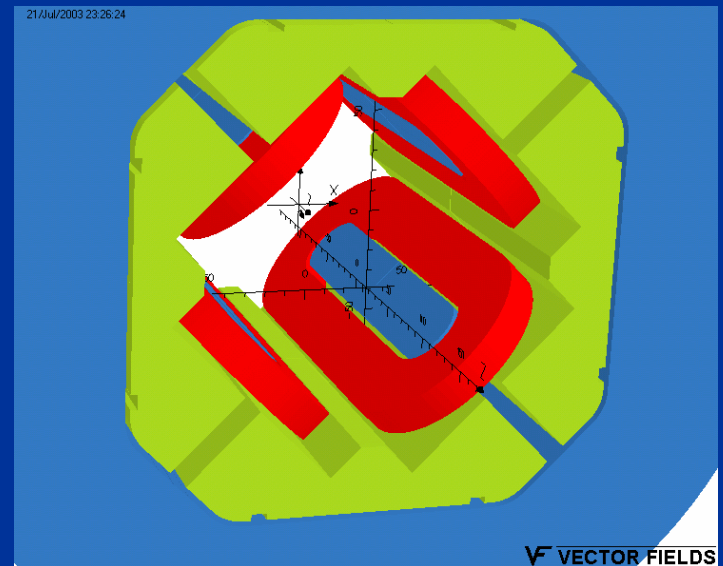
Coil Parameters (SM):

- 20 strands, 0.7 mm diam.
- 20 turn double-pancake

Magnet Parameters:

- Aperture 12 cm, length 30 cm
- Peak field ~ 10 T
- Gradient ~ 100 T/m

Gradient can be significantly increased by stacking 2 SM coils per quadrant

Replace iron pole with non-magnetic to reduce saturation effects

Support Structure

Mechanical support by yoke and shell pre-stressed using bladder & key

- Successfully used for very high field Nb_3Sn dipoles
- No pre-stress overshoot during magnet assembly
- Accurate pre-stress control during assembly
- Fast assembly/disassembly, ideal R&D tool
- Compatible with all coil geometries
- Simple and cost-effective
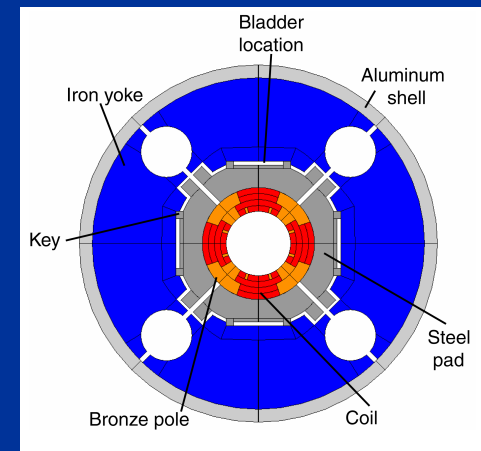
Experimental R&D issues:

- Application to quadrupole geometry $\rightarrow$ basic Nb_3Sn models
- Segmented shell for long magnets $\rightarrow$ mechanical models
- Geometric tolerances, reproducibility $\rightarrow$ racetrack quads

Quench Protection

Quench analysis for 2-layer and 4-layer designs (90 mm aperture):

- Heater: 26 μm thick stainless steel with distributed Cu plating
- Active sections are 100 mm long, 17% of total magnet length

PROTECTION SYSTEM PARAMETERS

Design	Voltage V	Capacitance mF	RC const. ms	G_{ss} T/m	T_{peak} K
Two-layer	440	13.2	26	245	200
Four-layer	750	6.2	23	266	300

ASC-02, Houston, August 2002

New analysis tools available - experiments are needed to verify results

Recent SM-05 test indicated good tolerance to high temperature/stress

Summary

<u>Phase I: Two years to address basic design and technology questions</u>

Wide range of issues to be covered:

- Define preliminary values/ranges for the main parameters

- Magnetic and mechanical analysis for different options

- Quench performance and training: basic magnet models

- Field quality: analysis, basic models, SM/racetrack quads

- Conductor & materials: conductor R&D, SM tests (*D. Dietderich*)

- Thermal/radiation studies: analysis + SM tests (*S. Caspi*)